Building-Integrated Rooftop Greenhouses: An Energy and Environmental Assessment in the Mediterranean Context

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Abstract

A sustainable and secure food supply within a low-carbon and resilient infrastructure is encapsulated in several of The United Nations' 17 sustainable development goals. The integration of urban agriculture in buildings can offer improved efficiencies; in recognition of this, the first south European example of a fully integrated rooftop greenhouse (iRTG) was designed and incorporated into the ICTA-ICP building by the Autonomous University of Barcelona. This design seeks to interchange heat, CO_2 and rainwater between the building and its rooftop greenhouse. Average air temperatures for 2015 in the iRTG were 16.5°C (winter) and 25.79°C (summer), making the iRTG an ideal growing environment. Using detailed thermophysical fabric properties, 2015 site-specific weather data, exact control strategies and dynamic soil temperatures, the iRTG was modelled in EnergyPlus to assess the performance of an equivalent 'freestanding' greenhouse. The validated result shows that the thermal interchange between the iRTG and the ICTA-ICP building has considerable moderating effects on the iRTG's indoor climate; since average hourly temperatures in an equivalent freestanding greenhouse would have been 4.1°C colder in winter and 4.4°C warmer in summer under the 2015 climatic conditions. The simulation results demonstrate that the iRTG case study recycled 43.78 MWh of thermal energy (or 341.93 kWh/m^2/yr) from the main building in 2015. Assuming 100% energy conversion efficiency, compared to freestanding greenhouses heated with oil, gas or biomass systems, the iRTG delivered an equivalent carbon savings of 113.8, 82.4 or 5.5 kg.CO_2(eq)/m^2/yr, respectively, and economic savings of 19.63,15.88 or 17.33 €/m^2/yr, respectively. Under similar climatic conditions, this symbiosis between buildings and urban agriculture makes an iRTG an efficient resource-management model and supports the promotion of a new typology or concept of buildings with a nexus or symbiosis between energy efficiency and food production.

Keywords

Rooftop greenhouse, Building performance simulation, Measured energy data, Energy Plus, Energy-food nexus, Building-rooftop greenhouse symbiosis.

Abbreviations:

ICTA-ICP, Institute of Environmental Science and Technology (ICTA) and Catalan Institute of Paleontology (ICP).

iRTG, Integrated rooftop greenhouse

RTG, Rooftop greenhouse

UA, Urban agriculture

1 Introduction

Buildings account for approximately half of the world's primary energy consumption [1–3], and agriculture and food production are reported to consume between 13-15% of total energy in developed countries [4–6]. Greenhouses are one of the most energy-demanding components of the agricultural industry [7–9] because ideal climatic conditions are created by closely controlling internal temperature and humidity levels for satisfactory plant growth in central and northern Europe.

While the decarbonisations of these two sectors require different solutions, an interesting possibility exists with an urban agriculture concept in which additional efficiencies can be derived from the integration of buildings and food production. A rooftop greenhouse (RTG), whereby soil-free farming methods such as hydroponics or aeroponics [10–12] may be integrated into a building, is an example. Although considerable amounts of non-renewable energy are conventionally used to operate greenhouses in central Europe, an integrated method could help decarbonise greenhouse-based food production and promote more efficient and sustainable greenhouse heating [13,14]. Empirical data are missing in this area, and this has formed the foundation of this work: full annual results are presented for the operational characteristics of the world's first case of a fully-integrated rooftop greenhouse for scientific research. Within this article, ICTA-ICP refers to the entire building under study; the integrated rooftop greenhouse (iRTG) is used to refer to the rooftop greenhouse.

The objective of this paper is, therefore, (a) to report the measured annual data that outlines the symbiosis between the iRTG and the building in energy terms and (b) using computer simulation, to quantify the heating energy that iRTG has passively and actively recycled from the ICTA-ICP. The reduced environmental impact resulting from this integration is then calculated using kg.CO_2(eq)/m^2/yr as the index. In doing so, the advantages offered by the iRTG concept relative to a conventional freestanding greenhouse are highlighted. While reporting the first scientific case for support on the application and feasibility of an iRTG; the findings also redefine a unique typology or concept of building design that can have a nexus or symbiosis between energy efficiency and food production worldwide as a strategy in support of food security and green urbanism. While seeking to offer an original perspective on the theme of integration of greenhouses in buildings and demonstrating the viability of this concept, this work also highlights the need for further research in the adaptation of iRTG concept under various urban energy and operational systems and climatic conditions around the world.

1.1 Global urbanisation and the food challenge

The United Nations, in its 2010 perspective, noted that more people live in urban settings than in rural areas. The projection of this trend is that world urbanisation will increase from 50% in 2009 to 69% in 2050 [15]. A total of 75% of the EU population currently lives in cities, a percentage that is expected to rise to 80% by 2020 [16]. This high concentration of people in cities has major socio-economic ramifications, and food production and its supply and security requires closer examination [17].

According to figures provided by the Food and Agriculture Organization of the United Nations (FAO), almost a billion people suffer from malnutrition, and four hundred million are chronically undernourished [18]. Conversely, urbanisation has generated a two-pronged nutritional burden: nutritional deficiencies and the emergence of over-nutrition among vulnerable groups in urban areas [19]. In recognition of this, the concept of urban agriculture (UA) seeks to offer innovative solutions to ensure the environmental and economic sustainability of food supplies within urban contexts and also to promote food of high nutritional quality.

Urban agriculture ranges from entirely commercialised agricultural facilities to production at the household level [20] and usually complements rural agriculture [21]. Urban agriculture is a historical reality in developing countries [22,23], where even today 800 million people are engaged in urban agriculture, producing 15 to 20% of the world's food [24]. It is believed that 10-20% of the nutritional needs of families living in urban areas in developing countries are met by the consumption of fruits and vegetables from urban agriculture [21].

Because of its adaptability to any built environment and typology, urban agriculture’s benefits encompass economic, social and environmental elements [25]. In urban areas of relatively high residential density with mixed land use and limited access to green spaces for food production, rooftop greenhouses (RTGs) can provide the opportunity for cities to produce high-nutrient food with maximum efficiency, minimising production and transport costs and optimising space use in a built environment where buildings can foster food production.

1.2. Conventional greenhouses

Greenhouses, regardless of their degrees of complexity, attempt to provide ideal conditions for adequate plant growth throughout the year [26,27]. The principal regulated parameters are light, temperature, humidity and air quality [28–30]. The origin of the greenhouse goes back to ancient times. They were popular during 15th to 18th centuries in France, England and the Netherlands, but their use for commercial production began only in the mid-19th century, increasing after 1945 [26] and culminating in today's widespread deployment in Europe. More specifically, the estimate for the European Mediterranean region is more than 200,000 ha of in-use greenhouses in 2006 and 1,950,000 ha by 2010. Spain had 53,842 ha during 2005, and in 2009, Almería possessed a total of 27,000 ha [31].

Specifically, the Mediterranean area ecosystems have the characteristics of several regions in the world, such as southern Chile, California, the European Mediterranean basin, Cape Province in South Africa, and southwest Australia [32,33]. In the European Mediterranean basin, the development of Mediterranean horticulture was reshaped by the energy crisis in the 1970s, when low-cost plastics and local materials were used to build the first generation of widely deployed greenhouses. A basic Mediterranean greenhouse is characterised by large inner volumes within a low-cost structure (i.e., low-cost polyethylene roof and walls), total transparency, natural ventilation, no heating, limited use of climate control systems, and stability with respect to wind and thermal screens [34,35]. The seasonal operational regime of Mediterranean greenhouses seeks the maximisation of solar irradiation and the minimisation of thermal energy loss (autumn and winter), as well as the reduction of excess temperatures in spring and summer [36–38]. High temperatures and high solar radiation can affect the development of crops, especially tomatoes [39,40], so the use of shading and efficient ventilation systems is required. Natural ventilation is the most economical method to reduce excess heat build-up in greenhouses, but as it is totally dependent on external conditions, it may be insufficient [41]. The most efficient systems use electrically powered forced ventilation, which understandably require electricity estimated at 100,000 kWh annually per greenhouse hectare, under high outside temperatures and intense solar radiation (common summer conditions in Mediterranean countries); such systems use a static ventilation fan pressure of approximately 30 Pa on the leeside or the lee end of the greenhouse with two fans placed 8-10 m apart and an inlet opening on the opposite side of least 1.25 times the fan area and an air speed of 0. 5 m/s [37].

Generally, some energy use is unavoidable and results in energy accounting for 10–30 percent of total production costs (depending on the region). In Mediterranean areas, the annual energy consumption for space conditioning is 139–444 kWh/m^2, which arises from winter night heating requirements (and is increasingly being adopted [37]), although the majority of Mediterranean greenhouses remain unheated.

The high cost of energy, climate concerns and new environmental policies have brought about the challenge of reducing the energy input into the greenhouse system while maintaining or increasing production per unit of energy [37,42].

1.3 Energy and food production in buildings

Modern cities are unfortunately dependent for the most part on a consistent supply of fossil fuels, and the urban lifestyle is becoming more energy-intensive worldwide [43]. Global demand for fossil fuels has risen more rapidly than production; in the build-up to 2014, energy use worldwide grew by one-third, driven primarily by developing areas such as India, China, Africa, the Middle East and Southeast Asia [44].

The energy used by the building sector continues to increase; worldwide, 30-40% of all primary energy is used in buildings [45]. One third of energy-related CO_2 emissions and two thirds of halocarbon emissions worldwide are attributed to buildings [46]. Electricity consumption in the commercial building sector doubled between 1980 and 2000 and is expected to increase by another 50% by 2025 [47]. Nonetheless, the Intergovernmental Panel on Climate Change indicates that buildings provide the most economic mitigation potential for reducing CO_2 emissions, with a global potential of cost-effectively reducing approximately 29% of the projected baseline emissions by 2020 in the residential and commercial sectors [48].

On the other hand, food supply to urban areas is a complex issue and a major energy consumer. The flow of food to cities follows a complex and linear model [10] defined by importing resources and exporting emissions, leading to high lifecycle utilisation per kg food unit of energy resources, waste and CO_2 emissions [49]. Where the concept of food production and building energy use has been united is in the use of the rooftop greenhouse (RTG) in Mediterranean cities; these have reduced building cooling and heating loads due to improved roof insulation, with reductions of up to 40 percent being reported for specific case studies [50].

The RTG concept has also been adapted in urban areas of Canada and the US, with examples including Lufa Farms (31,000 m^2 RTG in Montreal), The Vinegar Factory (830 m^2 RTG in Manhattan, NYC), Gotham Greens (15,000 m^2 RTG in New York) [51,52], and Sky vegetables (743 m^2) [53] and The Greenhouse (130 m^2) on the roof of Public School 333 [54], both in NYC. Also in NYC, the Arbor House with a 1000 m^2 greenhouse, using waste heat from below to heat a greenhouse building [55], captures 225 MWh / year of waste heat (26 kW avg). Research or social benefits have remained the driving forces for

RTG adaption in other countries; for example, Japan, specifically Tokyo, has developed Pasona HQ Tokyo Urban Farm (4,000 m^2 RTG) [56]. In Europe, Germany has some examples of implementation (In Farming of Fraunhofer, UMSICHT) [57]; the United Kingdom is currently constructing the new Urban Science Building at Newcastle University with a rooftop greenhouse planned [58], and Urban farmers in Switzerland (250 m^2) and the opening in 2016 in The Hague of the UF002 De Schilde (1900 m^2) [59] are also examples. Spain has the first building designed principally from the start to have an integrated building RTG (i-RTG), the ICTA-iRTG at the Autonomous University of Barcelona (UAB) [60]. The driving design principles were the creation of a building that enabled a synergetic relationship between food production and building management by recycling and integration of energy, CO_2 and water. Such a symbiosis is hoped to reduce the environmental impacts of buildings and ultimately cities. Inaugurated in 2014, this integrated greenhouse is producing four crops per year: two crops of tomatoes "*cor de bou*" (ox heart at a productivity rate of 16.2 kg per m^2) and two intermediate crops of lettuce. This innovative agricultural production system showcases how the building integration of a rooftop greenhouse (i-RTG) improves a building 'metabolism' by the direct flow exchange of energy, water and CO_2 [60].

1.4 The iRTG concept

The *Integrated Rooftop Greenhouse* (iRTG) is presented from an industrial ecology perspective as a system that incorporates urban agriculture into new or existing building rooftops in the city and consists of a greenhouse interconnected with its host building in terms of energy, water and CO_2 flows. As a new approach to sustainable urban food production, iRTG is based on four main pillars: (1) the incorporation of the concept of symbiosis between a rooftop greenhouse and the building by means of reusing residual resource flows (energy, water and CO_2), (2) the inter-connectivity of resource flows between iRTG and the building, in that the greenhouse is not an isolated element outside the main building envelope, but an integral part that requires consideration at the concept stage of building design, (3) environmental impact reduction and high energy efficiency as a critical concept, (4) facilitation of the production of quality food using building rooftops and generation of food production self- sufficiency in the urban context. Given the global need for responsible energy consumption in buildings and the urgency to secure food supplies, the contribution of this project is principally a design concept that creates a nexus or symbiosis between building energy flow and food production. Thus, the expansions of cities can be seen as an opportunity and not as an obstacle to maintain a secure food supply and energy efficiency.

The iRTG concept seeks to generate changes in the current conception of buildings as unproductive elements. Through iRTG, a building can be viewed as an element that, in addition to meeting the need for cover and protection, has the ability to support food production - regardless of its location around the world. Megacities (Shanghai, Mexico City, Osaka, Beijing, NYC and others) and developing cities have considerable artificialised areas and huge populations; the development of iRTG's affords the opportunity to produce and consume zero km vegetables with no increases in the energy consumptions of the buildings. That is, the concept of iRTG seeks to change the heterotrophic ecosystem of cities to an autotrophic urban ecosystem that does not require food imports from rural areas.

Despite the various benefits that can derive from the iRTG, there are only a limited number of studies around the world that address the issue, and these are from a mostly theoretical point of view. In Singapore, Astee (2010)[61] explored the feasibility of the implementation of an iRTG for growing vegetables in blocks of public housing in the city of Tampines; in New York, the architectural firm Kiss + Cathcart Architects provides the services of integrating food production into the building through hydroponics farming systems, though there is no information on actual cases [62]. In Brussels, the architectural firm Lateral Thinking Factory has proposed the theoretical design of an Integrated Building Greenhouse in the city of Louvain la Neuve, but the information is limited [63]. In Berlin, the Watergy Prototype 2 is being built, in which the greenhouse provides fruit by utilising the residual air of the building [64]. To date however, the only case designed and built for scientific research in urban agriculture is the ICTA-iRTG. Part of the importance of this case study lies in it being the only scientifically documented case that provides current data for comparison with other urban agriculture projects.

2 The case-study building

2.1 Overview

Located at the Autonomous University of Barcelona (UAB) campus (Bellaterra, Barcelona), the ICTA-ICP building (see Fig. 1) houses the headquarters of the Institute of Environmental Science and Technology (ICTA) and the Catalan Institute of Paleontology (ICP). The building was awarded LEED-Gold® certification (Leadership in Energy & Environmental Design) by the U.S. Green Building Council for its building-integrated agriculture philosophy, multifunctionality and passive systems that promote energy efficiency.

The building has a surface area of 7,200 m^2 distributed over 7 floors (5 levels above ground and 2 below). The two sub-ground levels are used for car parking and storage, while the first four levels above ground are equipped with offices, laboratories and common areas; and the fifth level houses four greenhouses for food production (measuring 128 m^2 each). Currently, only two of the four greenhouses are functional; this work reports data from one of these (referred to as the iRTG). The main structure and floors of the ICTA-ICP building are of reinforced concrete; the internal walls are recycled wood, and the roof and outer skins are made of polycarbonate, which facilitates an ideal environment for crop growth and daylighting the interior spaces.

The translucent nature of the building fabric facilitates passive heating in winter and aids displacement ventilation during summer (via 4 internal atriums and a double-skin facade). Displacement natural ventilation is facilitated through the opening of windows and skylights in the building outer skin. The ventilation simply renews the air as outer skin inlets allow fresh intake to travel horizontally into offices (via internal windows) and rise vertically via four internal atria before exhausting through the skylights (zenith ventilation). A concrete structure with high thermal inertia, coupled with building passive comfort systems, maintains a thermal anchor to minimise the active heating and cooling input of a ground-source heat pump (only to the internal workspaces and the laboratories). The iRTG does not have designated mechanical heating but, as outlined in the next section, benefits from the building's thermal stability. Its integration with the building is unidirectional (from building to greenhouse only). In this sense, the iRTG utilises exhaust air from the building for heating; the higher CO_2 concentration and humidity of this residual air also act as natural fertilisers to increase crop yields. The integration is direct if the residual air comes from laboratories (discharged directly into the iRTG via service ducts) or indirect if it comes from the common areas of the building (arriving into the iRTG via four atria).

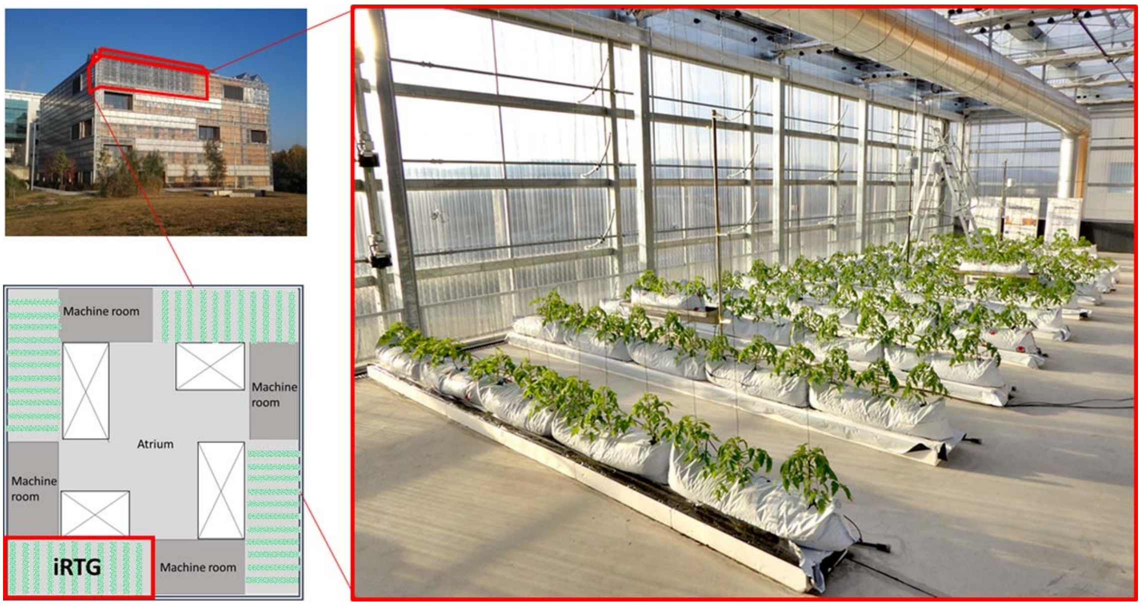

Figure 1 The ICTA-ICP building and the iRTG.

The iRTG greenhouse has modifications in form and building materials compared to the standard typology of traditional Mediterranean greenhouses to reflect its building-integrated nature. To comply with the Spanish Technical Edification Code (CTE) (RD 314/2006 (BOE 2006)) and fire safety laws (RD 2267/2004 (BOE 2004), Law 3/2010 (BOE 2010), the greenhouse galvanised steel structure was reinforced to withstand horizontal wind loads. Polycarbonate sheeting was used for the roof and walls because of its high solar transmittance.

The iRTG reported in this work has an area of 128 m^2 (6.55 m wide × 19.55 m long) with a two-span gable roof with 45º roof slopes (4.20 m high at the gutter and 5.80 m at the ridge). Awning windows mounted on sidewalls with a maximum opening angle of 45 degrees provide ventilation. The crop area is 84.34 m^2 and achieved a total production of 989 kg of tomatoes during the spring-summer period, 85% of which met commercial product requirements (with the remainder edible but not marketable). The greenhouse uses a thermal screen and low-density polyethylene (LDPE) curtains to both improve internal heat conditions and insulate the space from the rest the building and excessive influence of the outer skin. The thermal screen is similar to those deployed across the Mediterranean region to reduce incident solar radiation. Both the curtains and the thermal screen are operated automatically as a function of the temperature inside the greenhouse.

2.2 Thermal exchanges and controls

There are two thermal interaction paths between the iRTG and the building: the ventilation air from occupied spaces delivered to iRTG via air handling units (AHUs) and the displacement ventilation and air heated by solar radiation rising through the double skin cavity (that terminates at the iRTG - see Fig. 2).

The objective is that the cumulative effect of these heat transfers provide the iRTG with optimal thermal conditions (14-26°C) for Mediterranean horticultural crop production in a closed system throughout the year [65].

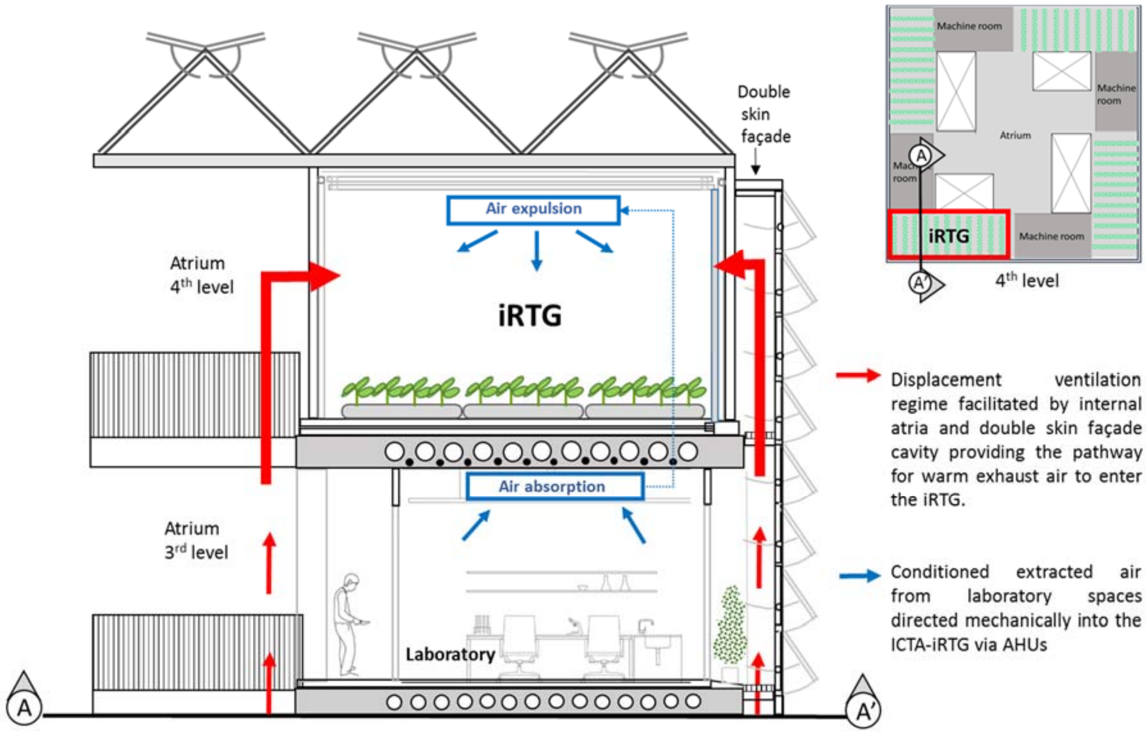

Figure 2 Three main flow paths for heat exchange between the ICTA building and the iRTG.

A set of 5 control schedules administer heating, cooling and window openings to optimise energy use to reflect seasonal and temperature requirements within the work areas (see Table 1). The laboratories are exempt from this schedule as they have changing thermal requirements based on ongoing research.

Table 1. Operational characteristics of ICTA building

Building mode	**Season**	**Date**	**Heating or cooling**
1- Winter	Winter	1 Dec. - 31 Mar.	Yes
2-Intermediate A	Spring	1 Apr. - 31 May.	No
3-Summer	Summer	1 Jun. - 30 Sept.	Yes
4 -Intermediate B	Autumn	1 Oct. - 30 Nov.	No

5- Passive mode	Weekends and holidays	All year	No
Laboratories	All year	(Depends on ongoing research)	Depends on ongoing research

At any point in the annual calendar, the ICTA-ICP building has 5 internal climates adapted to the functions of the spaces:

1- Laboratories, with heating/cooling to achieve a temperature range of 21-25°C to satisfy the changing needs of lab work.
2- Workspaces and offices, with heating/cooling and a temperature range of 17-26°C, depending on the season and the HVAC mode of operation.
3- Communal spaces, unheated/uncooled; the temperature is allowed to fluctuate with the season.
4- iRTG, unheated/uncooled; the temperature range varies as a function of the outside conditions and thermal interactions outlined in Fig. 2.
5- Parking and underground cellars, in freefloat mode; their temperature ranges vary as a function of outside conditions.

2.3 Monitoring tools

Two independent and complementary monitoring systems are instrumented in iRTG that were specified and programmed exclusively for this space: Siemens control software and a Campbell continuous data acquisition system. The Siemens software offers independent controls of the ICTA-ICP building and the iRTG thermal condition. Sensors and probes inside and outside the building continuously collect temperature, humidity, air quality, solar radiation and air velocity data, allowing the system to make automated decisions and interventions. The researchers are able to override automated controls and adjust the settings in response to user and crop requirements (i.e., overriding the opening of windows, temperature set points, greenhouse solar covers, etc.).

The Campbell data acquisition system comprises 12 temperature probes (Campbell 107 with an accuracy of ±0.18°C), 3 combined temperature and humidity probes (Campbell CS215 with accuracies of ±0.3°C and ±2%, respectively), 2 pyranometers (Campbell LP02 with expected accuracy for daily sums of ±10%) and 2 surface-temperature probes (Campbell 110PV with an accuracy of ±0.2°C) for energy monitoring. Additional Campbell probes also include sensors that monitor air quality, pH and conductivity of irrigation water. A data logger (Campbell CR3000 with ±0.04% of accuracy) takes measurements every 5 s and records the averages at 10 min intervals.

All sensors were pre-calibrated by Campbell. External data are obtained from the meteorological station of the building and are checked/compared with Sabadell Agricultural Park weather station (part of the Meteorological Service of Catalonia data) 5 km from iRTG. The meteorological station provides hourly averaged values.

All these probes are evenly distributed on four vertical supports that are erected at 0.40 m, 1.20 m, 1.70 m and 2.20 m above the iRTG floor level (see Fig. 3). Each vertical support has three temperature probes and a combined temperature and RH probe. The supports are located inside the iRTG and in the upper atrium of the ICTA-ICP building.

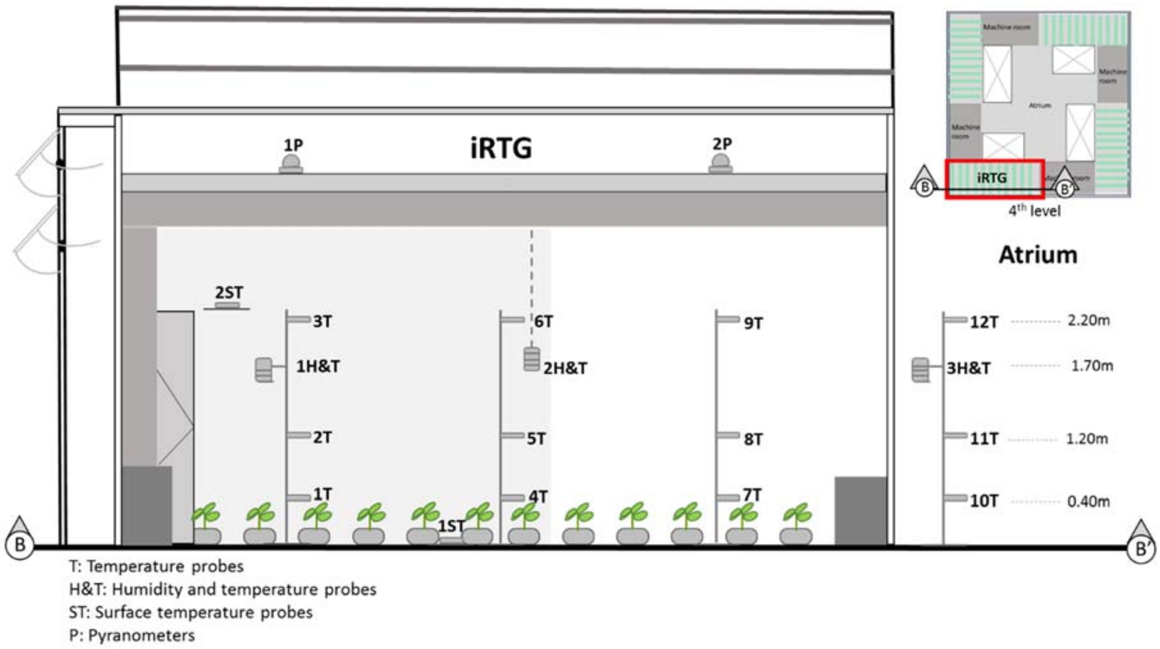

Figure 3 Probe locations within the iRTG and atrium spaces.

3 Simulation Method

3.1 Purpose and software description

To highlight the operational energy and indoor-climate benefits derived from the integration of the iRTG greenhouse with the ICTA-ICP building, two virtual models were created; the first is a complete model of ICTA-ICP building to validate building and model fidelity, and the second is a 'freestanding' virtual model of the iRTG to quantify the heating loads of an equivalent but freestanding greenhouse (see Fig. 4). Detailed iRTG fabric thermo-physical properties and exact operational regimes provided parameter input into

Design Builder version 4.6 (used to create the iRTG geometry). The completed Design Builder model was used to create the input data file (IDF) for EnergyPlus (E+) Version 8.4, which enabled the energy simulation. E+ was selected because of the following:

1- The E+ weather statistics and conversions program allow the creation of 2015 weather files using ICTA-ICP site-specific dry bulb air temperatures and relative humidity. However, solar irradiation, wind and precipitation data were compiled using the 2015 Sabadell station.
2- The transparent nature of the ICTA-iRTG fabric leads to substantial space-climate interactions. E+ has the ability to accept the detailed spectral optical properties of the transparent fabric and user-specified window and shading controls (see Table 2).
3- Schedule: the file facility in E+ can accept hourly space target temperatures, allowing the accurate replication of the iRTG internal climate and subsequent heating demand.
4- Zone and soil heat exchange are critical in simulating the performance of a greenhouse; KIVA software version 0.3 [66] was used to generate hourly soil temperatures and informed the freestanding iRTG model.
5- E+ has been demonstrated to have high accuracies for internal temperatures and load predictions [67].

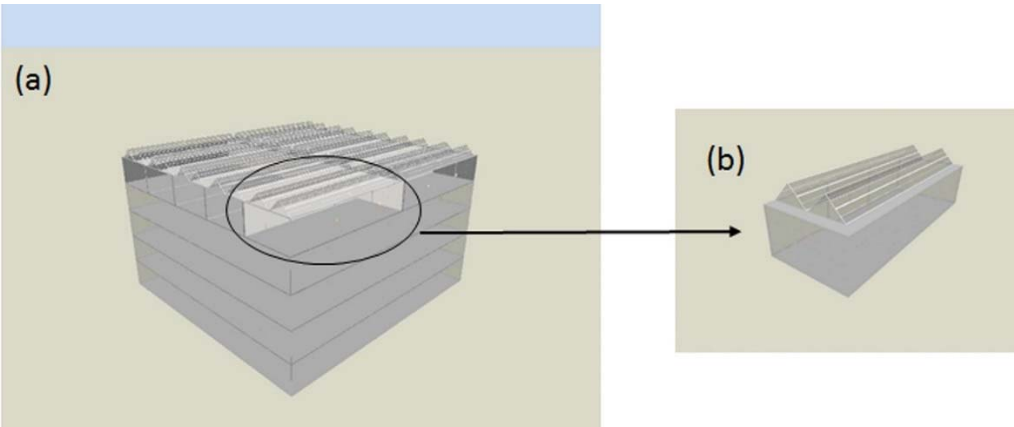

Figure 4 (a) Design Builder model of the ICTA-ICP building to validate model prediction accuracy, (b) freestanding iRTG used to examine freestanding greenhouse conditions.

The manufacturer's literature and (where unavailable) the Cambridge University 2015 CES database and 2013 ASHRAE Handbook (Fundamentals) were consulted to compile detailed input parameters (see Appendix Table A1). Similarly, the occupancy pattern, artificial lighting arrangement, exact operating schedules for the windows and retractable aluminised screen of the iRTG informed both the validation and freestanding modelling work.

Table 2. Opening regimes of the iRTG windows and retractable aluminised screen.

	Internal temperature (ºC)	Opening
Roof Windows	22	10°
	23	20°
	24	30°
	27	45° [1]
Facade Windows	22	5°
	23	10°
	24	20°
	27	45° [1]
Reflective aluminised screen[4]	31	25%[2]
	31,8	50% [2]
	32,6	75% [2]
	34	100% [2]
	<16	100% [3]

[1] Maximum opening angle

[2] Summer-only operations to prevent overheating

[3] Winter-only closure to prevent thermal inversion (thermal loss)

[4] Reflective screen opening refers to the screen expanding to cover the iRTG below

3.2 Optical properties of translucent material

Altogether, 111 data entry points were used to describe the optical properties of the translucent fabric component of the iRTG using the manufacturer's data (wavelength range: 125-15,000 nm). This proprietary corrugated polycarbonate sheet is designed for maximum light transmission in the visible spectrum. Full spectral properties were used in E+ within a bilinear interpolation using Glazing's U-Value and Solar Heat Gain Coefficient (SHGC) to calculate solar transmittance at normal incidence. Angular performance was then calculated in 10° increments and stored in E+ and interpolated for in-between values during the simulations [68].

3.3 Crop transpiration coefficient

Crop transpiration plays a significant role in the greenhouse climate. During the day, the crop canopy absorbs a significant amount of the solar radiation it receives and uses this energy to evaporate water through transpiration. As a result, the temperature of the greenhouse air decreases, and its humidity content increases.

Several formulae have been used in the literature to calculate crop transpiration. Bonachela et al. (2006) [69] provided an empirical formula for Mediterranean greenhouses as follows:

$$\mathrm{ET_0} = (0.288 + 0.0019 \times \mathrm{JD})\mathrm{Go} \times \tau \quad \text{(For Julian days (JD)} \leq 220) \qquad [1]$$

$$\mathrm{ET_0} = (1.339 - 0.00288 \times \mathrm{JD})\ \mathrm{Go} \times \tau \quad \text{(For Julian days (JD)} > 220) \qquad [2]$$

where ET_0 is the transpiration of a reference crop defined as an extensive surface of green well-watered grass. Transpiration of other crops is derived by multiplying reference transpiration by specific crop coefficients. JD is the Julian Day number, G_0 is the outside solar radiation, and t is the overall greenhouse transmissivity to solar radiation. By using the JD for every central day of each month, it was possible to calculate the percentage of outside solar radiation that the crop used for transpiration, which forms the plant cooling effect. The Energy Management System in E+ was used to create control logic that uses an independent variable (i.e., solar irradiance arriving in the greenhouse) to compute corresponding plant transpiration cooling capacity using equations 1 and 2.

3.4 Surface convective coefficients

Considerable uncertainties exist in convective heat transfer coefficient (CHTC) values applied in building models that are transferred into and cause large errors in the energy-prediction results [70]. Given its significance, an outline of the calculation selection is covered here. CHTC is a major energy transfer mechanism, and a multitude of different analytical and experimental methods exist that describe internal or external surface coefficients at various air velocity profiles and surface geometries. The rate by which an internal building surface loses heat is predominantly dictated by its convective coefficients, whereas external surface heat loss is dominated by air movements.

E+ documentation recommends the DOE-2 model to calculate CHTC values for smooth vertical surfaces with windward or leeward orientations in low-rise buildings, which closely represents the iRTG structure. DOE-2 is a hybrid full-scale CHTC model that combines the MoWiTT [71] and BLAST [19] models to dynamically calculate external CHTC using the following:

$$h_{c,ext} = \sqrt{h_{c,nat}^2 + \left(aV_{10}^b\right)^2} \quad [3]$$

$$h_{c,nat} = 9.482 \frac{(|T_s - T_a|)^{1/3}}{7.238 - |\cos ø|} \quad \text{(for ascending flows (Ts>Ta))} \quad [4]$$

$$h_{c,nat} = 1.810 \frac{(|T_s - T_a|)^{1/3}}{1.382 + |\cos ø|} \quad \text{(for descending flows (Ts<Ta))} \quad [5]$$

where $H_{c,ext}$ denotes external CHTC, $h_{c,nat}$ accounts for buoyancy-driven flows (W/m^{2}K), T_s and T_a are surface and air temperatures (°C), and ø is the surface plane slope angle in relation to the ground plane (°), which makes equations 4 and 5 equal at 90° (for a vertical wall). a and b are constants outlined in Table 3, and V_{10} represents the undisturbed wind speed measured at 10 m above ground level (m/s). E+ calculates the roof CHTC in the same manner.

Interior CHTC was dynamically calculated using the TARP [72] method that computes the sum of forced and natural convection components, with the natural component derived from expressions 4 and 5, while the forced component is as follows:

$$h_{c,for} = 2.537\, W_f R_f \left(\frac{PV_f}{A}\right)^2 \quad [6]$$

where $h_{c,\,for}$ is the forced CHTC component (W/m^{2}K), W_f is the wind-direction modifier, R_f is the surface-roughness multiplier, and P and A are the perimeter and area of the surface (m and m^2), respectively.

Table 3. Constant parameters for MoWiTT model.

Surface orientation	a	b
Windward	2.38 ± 0.036	0.89 ± 0.009
Leeward	2.36 ± 0.098	0.617 ± 0.017

3.5 Model validation

For model validation, site-specific direct and diffused solar irradiance, outdoor temperature and humidity and sky conditions were used within a complete model of the ICTA-ICP building with actual indoor temperatures and operational regimes. The complete building model enables accounting for the impact of the main building structure and envelope on the iRTG. A succession of 17 models, each with incremental adjustments, were used to best satisfy ASHRAE Guideline 14 (2002) on model validation using actual and simulated hourly data [73]. This entailed determining the two dimensionless indicators of errors, mean bias error (MBE) and cumulative variation of root-mean-square error (CV (RMSE)) using the following:

$$MBE = \frac{\sum_{i=1}^{N_i} (M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad [7]$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i} [(M_i - S_i)^2 / N_i]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \quad [8]$$

where M_i and S_i are the measured and simulated data, respectively, at instance i, and N_i is the count of the number of values used in the calculation. The ASHRAE building model calibration limits on hourly data are ±10% (for MBE) and <30% (for CV (RMSE)).

4 Results and discussion

4.1 iRTG annual space condition

The iRTG temperature data compiled by monitoring systems for the first operational year are summarised in Table 4. This captures seasonal averages, as well as maximum and minimum temperatures, from December 2014 to December 2015. Seasonal average temperatures range from 16.5°C in winter to 25.9°C in summer, with a winter minimum of 6.3°C and a summer maximum of 39.7°C. Average iRTG temperatures are, therefore, within the FAO's recommended optimum average range of 14-26°C and satisfy the Mediterranean horticultural closed systems recommendations.

Table 4. Weekly iRTG and outdoor average temperatures in each season of 2015.

	Winter 21 Dec. 2014 19 Mar. 2015		**Spring** 20 Mar. 2015 20 Jun. 2015		**Summer** 21 Jun. 2015 22 Sept. 2015		**Autumn** 23 Sept. 2015 20 Dec. 2015	
	ICTA-iRTG	Outdoor	ICTA-iRTG	Outdoor	ICTA-iRTG	Outdoor	ICTA-iRTG	Outdoor
Average Temperature (°C)	**16.5**	**7.5**	**21.6**	**16.7**	**25.9**	**24.4**	**18.8**	**13.1**
Maximum Temperature (°C)	29.6	22.8	34.5	34.6	39.7	38.1	31.0	29.2
Minimum Temperature (°C)	6.3	-3.6	13.5	1.2	15.7	11.8	10.2	-2.3

During the coldest 2015 winter night when the temperature fell to -3.6°C, the corresponding iRTG temperature (also its lowest recorded temperature) was 6.3°C. This is lower than the recommended value of 14 °C, but higher, than the minimum winter night temperatures measured in conventional greenhouses in the Mediterranean area (note that average iRTG winter temperatures are 9°C warmer than the average external temperatures). This significant difference is due largely to the thermal inertia provided by the concrete floor of the greenhouse and the use of the thermal screen and LDPE curtains at night, which minimise thermal loss.

Conventional Mediterranean greenhouses do not commonly deploy heating [74], so the nocturnal temperatures in winter are usually the same or lower than those recorded outside [75,76]; this phenomenon does not occur in the iRTG. In this sense, the iRTG has a notable thermal advantage over the conventional greenhouses of the Mediterranean region during winter nights; this advantage translates into energy savings and better thermal conditions for crops in winter.

The iRTG weekly average summer temperature was 25.9 °C, with a maximum of 39.7°C (the outside weekly average and maximum were 24.4°C and 38.1°C, respectively). This is common in passive greenhouses in the Mediterranean region, due to the hot summers where mostly natural ventilation is used to dissipate the accumulated internal heat. As a last resort in passive greenhouses, shade nets are used to reduce the intensity of solar radiation received by the crop [26].

The risk of crop failure due to overheating (T_a>40°C) could be mitigated through a rapid building control response to open greenhouse shutters for ventilation or closing the sun screen cover to reduce solar radiation. However, because of the integrated nature of the iRTG with the building, the thermal response would be slower. Therefore, given that 2015 was the first operational year, lack of experience with the controls meant that adapting to the outside weather conditions occasionally did not occur at the desired speed. The knowledge of the thermal behaviour of the iRTG gained during 2015 will be instrumental in solving the overheating challenge during its second operational summer (2016).

During spring and autumn, the iRTG had the most stable average temperatures (21.6 °C and 18.8°C, respectively), which are ideal for growing crops in Mediterranean areas. Despite having ideal thermal conditions, the intensity of solar radiation is not at its best, especially in autumn.

4.2 Annual thermal performance (4 seasons in 2015)

To expand the scope of examination beyond the iRTG, it is necessary to explore the influence of the temperature of the rest of the building (common spaces without heating) on iRTG's thermal behaviour. Fig. 5 outlines different average temperatures across 4 seasons during 2015 recorded in the iRTG, in common spaces without heating (atrium) and the outdoor temperature.

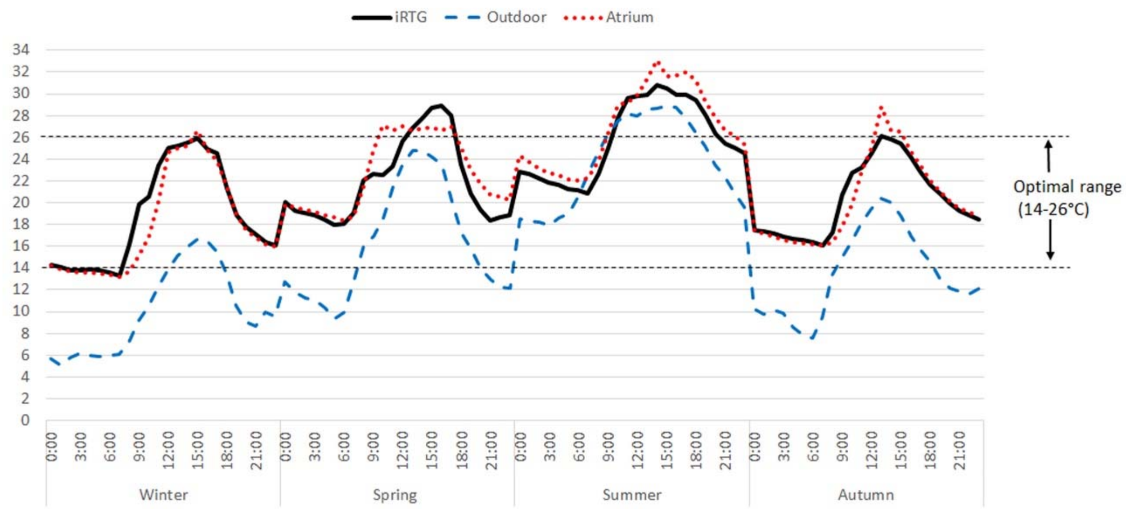

Figure 5 Averaged hourly 2015 temperatures of 3 probe stations positioned inside the iRTG, the atrium and externally.

The 2015 thermal behaviour of the iRTG more closely resembles the atrium of the building than the outside conditions. Note that the atrium is open to the communal areas that are not conditioned. The conditioned offices and laboratories, however, interact with communal areas when doors and windows are left open. The greatest difference between the iRTG and the outside temperatures is in winter and autumn, due largely to the interaction between the building and the iRTG. The resulting 'elevated temperatures' in the iRTG offer an advantage over conventional greenhouses, which experience indoor temperatures sub-optimal for crop development during colder months.

4.3 Model validation

Figures 6 and 7 outline actual versus simulated hourly air temperature and humidity results for typical winter and summer weeks (using 2015 data) when the iRTG is modelled to replicate reality as a rooftop part of the ICTA-ICP building (Fig. 4-(a)). Respective MBE and CV(RMSE) values for air temperature are 2.6% and 11.5% and for humidity are 2.9% and 15.9%; MBE figures provide an indication of errors averaged to the mean of the measured values, but they suffer from the cancellation effect. The CV (RMSE) index, however, 'accumulates' errors and normalises them to the mean of the measured values, which explains the difference in magnitude of the reported error indices. An error is defined as the actual value subtracted from the model prediction (i.e., M_i-S_i) [77]. Overall, the largest model errors occur in the daytime (7 am-6 pm) under clear sky conditions when internal temperatures are on average over-predicted by 5.4%. The second largest errors are, similarly, temperatures in the absence of solar irradiation (night values) that are on average under-predicted by 5.24%. This suggests that the actual iRTG internal climate is more moderate than the E+ model prediction. One explanation is that the ICTA laboratories discharge their 'closely controlled' ventilation air into the iRTG. Recall from section 1-3 that the laboratory controls are adjusted to achieve 21-25°C in an ad-hoc manner to satisfy the daily research agenda, and this 'random' discharge of ventilation air into the iRTG cannot be matched exactly by the deterministic control schedules used in E+. In addition, researchers intervene to readjust the controls of the iRTG; that again departs from the deterministic E+ schedules of the iRTG model. Nonetheless, both the temperature and humidity results fall within ASHRAE guide 14 limits, and as per the concluding remarks of Royapoor et al. (2015), the model can be considered validated.

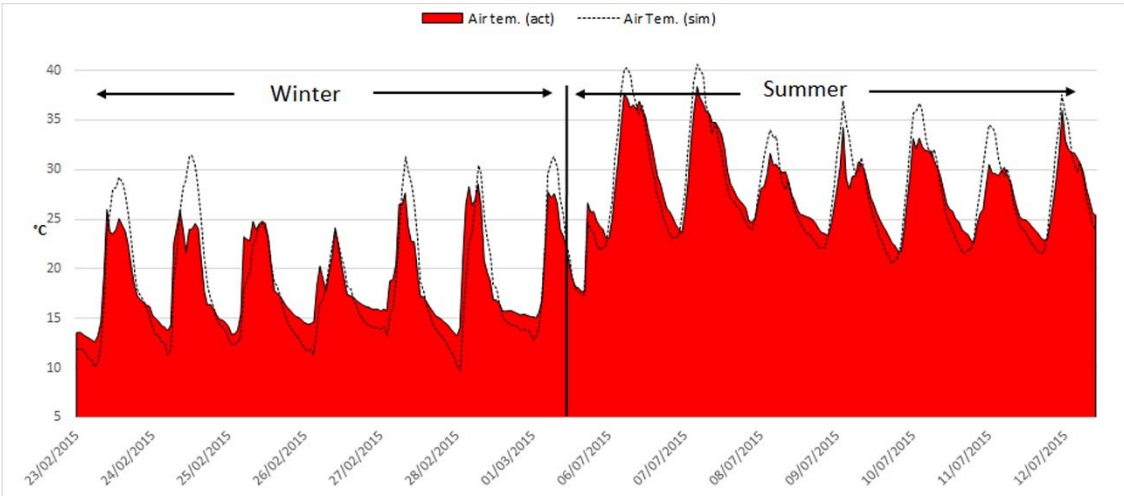

Figure 6 Hourly actual versus simulated air temperature results for the iRTG for winter and summer weeks.

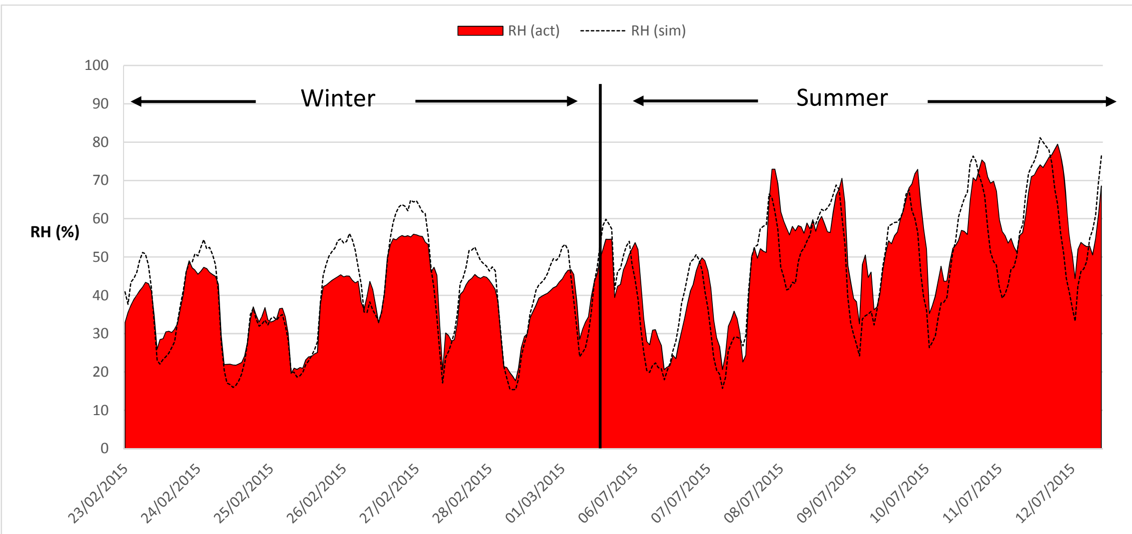

Figure 7 Hourly actual versus simulated humidity results for the iRTG for winter and summer weeks.

4.4 iRTG in a free-standing condition

This section reports the simulation results for an exact geometrical equivalent of the iRTG if it were a freestanding structure erected on soil and independent from the ICTA building. In doing so, this section first compares the annual indoor air temperatures of the actual iRTG with the freestanding model and secondly reports the heating energy required to maintain the minimum 2015 air temperatures logged in the actual iRTG.

Taking an optimum temperature range of 14-26 °C for the Mediterranean horticultural closed system context, in 2015, the actual iRTG indoor climate met this condition in over 76.3% of annual hours. The simulation result shows that under the same climatic conditions, an unheated freestanding structure identical to the iRTG would have met the optimum range in only 42.4% of the annual hours; if heated, it would satisfy the optimum range in 65.1% of annual hours (note that the heating target temperatures for the freestanding model were actual hourly temperatures recorded in the iRTG during 2015). If model validation errors are imposed on the results (i.e., correcting day over-predictions by -5.4% and night under-predictions by +5.24%), the freestanding models meet the optimum range of 14-26°C for 47.5% and 66.3% of the annual time in unheated and heated modes, respectively. This demonstrates that the error margins are too small to alter the results in a dramatic way. Fig. 8 is a graph of instances when 14-26°C optimum range is not met. As is evident, the freestanding greenhouse in both heated and unheated modes shows many more instances of overheating in summer.

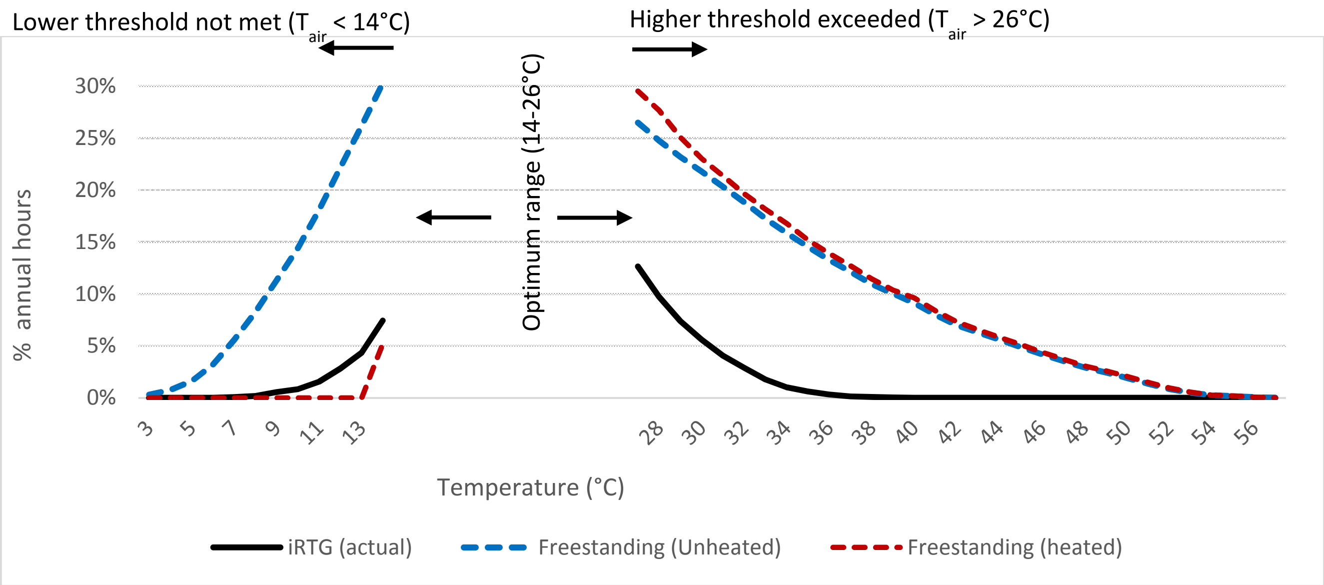

Figure 8 % annual time with space air temperature falling outside the optimum range.

Therefore, the moderating effect that the integration of the iRTG with the building has had is not limited to higher winter temperatures. The actual iRTG has additionally not suffered as many instances of overheating that a freestanding structure would have experienced, thanks largely to the building thermal inertia and cooler exhaust air discharged into the iRTG in the summer. This is also evident from the plot of annual hourly temperatures (Fig. 9) in which the freestanding model would have had winter lows of 2°C in the unheated mode and summer highs of approximately 45°C in both modes (this occurs at times of high solar irradiance and high external temperatures).

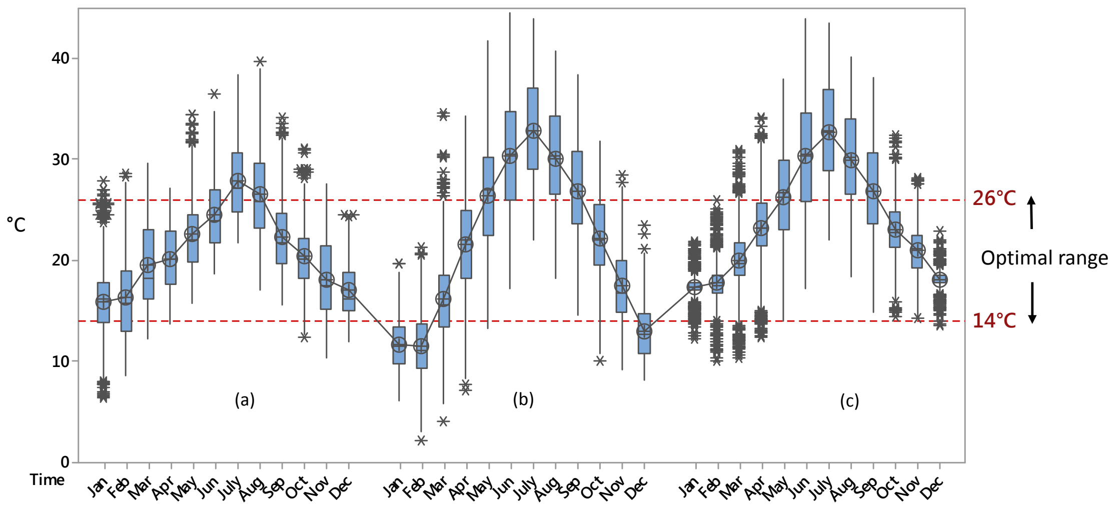

Figure 9 Hourly annual temperatures in (a) the actual iRTG (measured), (b) an unheated freestanding model of an iRTG (simulated) and (c) a heated freestanding model of an iRTG (simulated).

Fig. 10 is a plot of the hourly annual heating demand required to heat the freestanding model to achieve the minimum threshold temperatures recorded in the actual iRTG. Assuming a 100% fuel conversion efficiency, the total heating demand for the freestanding model would be 43.78 kWh under 2015 climatic conditions. This ideal heating requirement has a maximum of 66.62 kW with instances of heating required even in summer months (in early morning hours). This provides a scale of the total heating recycled by the actual iRTG from the ICTA-ICP building. Although the iRTG has also benefited from the summer cooling effect from the building, equivalent cooling loads were not calculated as this was deemed unrealistic in a commercial greenhouse context.

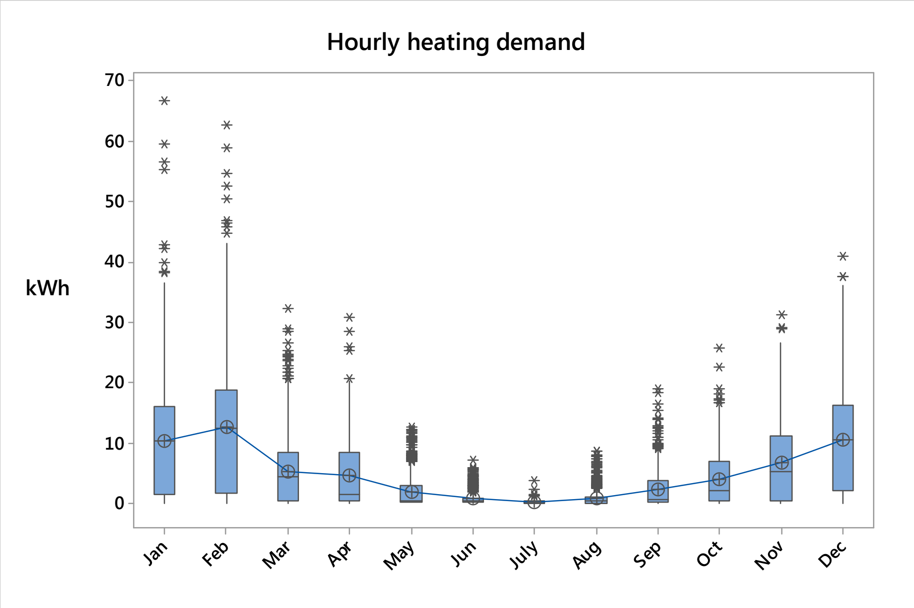

Figure 10 Hourly annual heating requirements assuming 100% fuel conversion efficiency.

Maintaining a 100% energy-conversion efficiency, the simulation results were used to calculate the financial and carbon savings of an iRTG relative to an equivalent heated greenhouse using associated carbon intensities derived from regional sources [78–80]. The results show that an oil boiler meeting the heating demands would produce 113.8 Kg.$CO_{2(eq)}$/m^2/yr, at a cost of 19.63 €/m^2/yr. A gas boiler would produce 82.4 Kg.$CO_{2(eq)}$/m^2/yr, costing 15.88 €/m^2/yr; finally, a biomass boiler would result in 5.5 Kg.$CO_{2(eq)}$/m^2/yr at a cost of 17.33 €/m^2/yr.

These economic and CO_2 savings demonstrate the feasibility of integrating greenhouses into buildings as a new strategy, forming a resilient and low-carbon civic infrastructure in which the capacity to meet urban food supplies exists locally, supporting food security and sovereignty of the most vulnerable sectors of the urban population. In doing so, the traditional idea of urban zones with inadequate green areas can be challenged because even when substantial concrete and masonry building surfaces exist, it is possible to re-function under-utilised rooftops for the cultivation of various fruits and vegetables in cities around the world, particularly in cities with growing populations, a lack of space for growth, a very large constructed area and a high dependence on importing vegetables, such as Shanghai, Beijing and Guangzhou in China and several cities in the USA, Japan and Canada.

5 Conclusions and future work

The urgency to reduce the environmental impact of civic life requires solutions that achieve greater efficiencies, in particular, by minimising waste and maximising the use of finite resources. The energy-intensive nature of agriculture and the built environment offers opportunities in which an integrated approach can lead to more efficient resource management. An iRTG at the ICTA-ICP building within the UAB university campus demonstrated an ideal closed system greenhouse facility in which (its first operational year) 16.2 kg/m^2 of *cor de bou* tomato and two successive crops of lettuce were produced in 2015. A validated model demonstrated that the integrated nature of the iRTG resulted in 341.93 kWh/m^2/yr of heating energy being 'recycled' from the rest of ICTA building; this is within 139–444 kWh/m^2/yr of the reported power requirements for heated Mediterranean greenhouses. Although the iRTG is not actively conditioned and has a transparent fabric, its internal temperatures are greatly stabilised through thermal 'coupling' with the rest of the ICTA building. This was evident as the actual recorded air temperatures within the iRTG were much closer to the recorded building thermal mass and indoor air temperatures than to the external climatic conditions. Validated simulation results also showed that under the same climatic conditions and control regimes, instances of 'sub-optimal' temperatures (outside the 14-26°C range) would have been 33.5% higher in a freestanding greenhouse (in the form of low winter and excessive summer temperatures). Eliminating limited instances of summer overheating altogether remains the main challenge for the iRTG research team; this highlights the need for detailed planning at the design stage and consistent monitoring after commissioning if similar building-integrated greenhouses are inaugurated elsewhere. While the empirical foundation of this paper relies on data from Southern Europe and specifically a Mediterranean context, the validated results offer a broader scope. Archetypes of buildings and climatic variations across the world can be exploited to enable building-integrated greenhouses to function adequately, and as such, pilot projects to verify the socio-economic and energy benefits of greenhouse integration in the urban space remain invaluable. At the same time, major conurbations across the U.S. (California in particular), southern Chile, Cape Province in South Africa, and the southwest of Australia all share ecosystem characteristics similar to the Mediterranean area in which the iRTG has been demonstrated as a viable concept. Future research will focus on the characterisation of bidirectional energy performance between the greenhouse and the building to quantify potential heating energy savings in the ICTA-ICP building derived from the rooftop greenhouse and to analyse the implementation of the iRTG concept in different geographical areas of the world where urban agriculture and improved energy efficiency in the built environment can be combined.

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Appendix

Table A1: Thermo-physical and surface properties of the fabric construction of the ICTA-iRTG model.

Clear Polycarbonate fabric material	Thickness (mm)	0.8 [1]
	Conductivity (W/mK)	0.2 [1]
	Solar transmittance	0.835 [1]
	External surface solar reflectance	0.075 [2]
	Internal surface solar reflectance	0.075 [2]
	Visible light transmittance	0.883 [1]
	External visible light reflectance	0.061 [2]
	Internal visible light reflectance	0.060 [2]
	Total Infrared transmittance	0.800 [1]
	External surface emissivity (IR)	0.900 [2]
	Internal Surface emissivity (IR)	0.900 [2]
	U-value (W/m^2K)	5.7 [1]
Galvanised Steel framing	Thickness (mm)	4 [1]
	Inside convective heat transfer coefficient (W/m^2K)	TARP [6]
	Internal radiative heat transfer coefficient (W/m^2K)	1.847 [2]
	External surface resistance (m^2K/W)	0.135 [2]
	External convective heat transfer coefficient (W/m^2K)	DOE-2 [6]
	External radiative heat transfer coefficient (W/m^2K)	1.71 [2]
	Surface resistance (m^2K/W)	0.04 [2]
	U-value (W/m^2K)	5.84 [2]
High-Density Polyethylene Floor cover	Thickness (mm)	0.65
	Thermal conductivity (W/m.K)	0.5
	Specific heat (J/Kg.K)	1800
	Density (Kg/m^2)	980

	Surface thermal absorbance	0.9
	Surface solar absorbance	0.7
	Internal Convective heat transfer coefficient (W/m^2K)	11.54
	U-value (W/m^2K)	2.45
Partition Polyethylene Curtains	Emissivity	0.69 [1]
	Transmissivity	0.19 [1]
	Reflectivity	0.12 [1]
Soil Condition [5]	Active thickness (mm)	490
	Conductivity (W/m.K)	1.28
	Specific heat (J/Kg.K)	880
	Density (Kg/m^2)	1460
	Thermal absorbance	0.9
	Solar absorbance	0.7
	Vapour resistivity (MNs/g)	10
	U-value (W/m^2K)	2.45
Other	Lighting (W/m^2)	3 [3]
	Occupant Density ($people/m^2$)	0.6 [4]
	Discharge coefficient for openable windows	0.65

Footnotes:

[1] Manufacturers product technical literature

[2] Cambridge University CES EduPack 2015 database (reference data)

[3] 6x T5 Fluorescents (60 W each) over a total area of 142 m^2

[4] A total of 30 half hourly visits by 3 to 5 researchers at various office hours

[5] ASHRAE Handbook -- Fundamentals - Physical Properties of Materials

[6] See method section

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